Operation of a Bayard–Alpert gauge in a uniform 0–0.16 tesla magnetic field[a)]

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The behavior of one widely used Bayard–Alpert ionization gauge in a magnetic field has been experimentally investigated for two cases: field orthogonal to, and parallel to the grid axis. Emission, grid and collector currents, and current to the wall surrounding the gauge were measured as functions of field magnitude and direction for N_2 in the pressure range 5×10^{-8} to 2×10^{-4} Pa. In addition to graphical presentation of these data, a qualitative description is given of the oscillatory components observed in the collector and wall currents. The data show that the zero-field gauge sensitivity can lead to large pressure measurement errors when operating the gauge in fields as weak as 0.005 T and that under certain conditions these errors may reasonably be accounted for by first determining gauge response as a function of field.

I. INTRODUCTION

Detailed experimental investigations have been carried out for ionization gauges in which an applied magnetic field is essential to their performance. See, for example, the Philips cold-cathode ionization gauge,[1] and related designs such as the hot-cathode magnetron gauge,[2] the cold-cathode inverted magnetron gauge,[3] and the Houston ionization gauge.[4] Some theoretical analysis pertinent to these magnetron type of gauges has been done by Twiss[5] and Redhead.[6] On the other hand, although they are not expressly designed for operation in a magnetic field, hot-cathode ionization gauges with the Bayard–Alpert (B–A) geometry are sometimes used for neutral gas density measurement in magnetic-confinement plasma fusion research,[7,8] because of their linearity over a very broad range and fast response to transients. Early works on the behavior of a B–A gauge in a magnetic field are those of Martin[9] and Normand.[10] Hammond and Riviere[11] examined the behavior of a B–A gauge modified by replacement of the linear filament with a circular one. More recently, Hseuh[12] carried out a detailed investigation for relatively weak fields ($\leqslant$0.006 T). The most recent work, that of Pickles and Hunt,[8] is concerned with gauge behavior in fairly strong fields of 0.3 to 0.7 T.

The present paper provides a much more detailed description, than has heretofore been available, of the behavior of one widely used commercial B–A gauge in a uniform magnetic field. The primary purpose here was to look for conditions under which intelligible gauge operation may be obtained.

II. APPARATUS AND PROCEDURE

The gauge under study, a flange-mounted nude B–A gauge [see Fig. 1(a)], was operated with grid bias at + 150 V, filament midpoint bias at + 50 V, and collector at ground potential (0 V). The dc filament heater current was adjusted to yield 1-mA emission current in zero magnetic field. The gauge is specified to be of nonmagnetic construction: 0.13-mm-diam tungsten collector wire, platinum–iridium alloy grid, molybdenum grid supports, and helical tungsten filaments. Remaining gauge parts are alumina and 304 stainless steel. A ceramic break (see Fig. 1) in the 35-mm-i.d. stainless-steel tubing connecting the gauge to the pump permitted measurement of current to the vacuum wall surrounding the gauge and biasing of the wall (normal wall bias was 0 V).

The magnetic field was produced by a pair of air-core electromagnets. For the case of fields perpendicular to the grid axis, the magnets rested on a rotatable platform and were equidistant from the platform rotation axis [see Fig. 1(a)], which coincided with the vertical axis ZZ′ of the gauge grid. The horizontal axis OO′ of the magnets' bore intersected the grid axis at its midpoint. For the case of magnetic field paral-

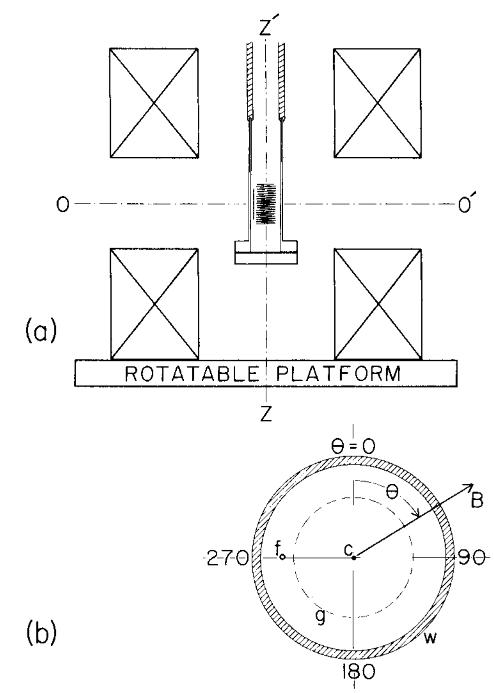

FIG. 1. (a) Placement of magnets and gauge for case in which field is perpendicular to grid axis. Magnetic field is parallel to horizontal axis OO′ of magnets. (b) Relation between direction of magnetic field **B**, magnet rotation angle θ, and gauge structure. Grid axis ZZ′ is perpendicular to plane of figure (b). At $\theta = 180°$, field is directed from collector to the unused filament. The filament *f* is represented by the small open circle (○).

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lel to grid axis, the magnets were repositioned to align the magnets' axis OO′ with ZZ′. Measurement of the field components in the central region between the magnets showed that the most uniform field occurred for the magnet spacing of about 15 cm used in this work. At this spacing, the field magnitude varied by no more than $\pm 3.5\%$ from its mean value and the field direction changed by less than $\pm 2°$ over the volume of space occupied by the gauge structure. The correspondence between direction of the magnetic field **B**, magnet platform rotation angle θ, and gauge structure is shown in Fig. 1(b).

Four quantities were measured as functions of field magnitude B and rotation angle θ: the collector current i_c, the grid current i_g, true emission current i_{em} (i.e., the current leaving the filament), and the wall current i_w. However, in the following sections discussion of the grid current is omitted because, within the precision of measurement (one part in 10^5), it was equal to the emission current, minus any electron current to the collector and/or wall. Filament heater voltage, measured at the gauge, and heater current were continuously monitored and found to be unaffected by either magnitude or direction of the applied field. The following data were obtained at a constant filament heater power of about 7.6 W.

III. DISCUSSION OF RESULTS

A. Effect of field magnitude and direction on currents

1. Magnetic field perpendicular to grid axis

The data shown in Figs. 2 and 3, obtained at a pressure of about 1×10^{-7} Pa N_2 equivalent, illustrate the principal effects of the field on the gauge currents for magnetic fields perpendicular to the grid axis. The effect on emission current is shown in the middle column of Fig. 2. As field magnitude is increased, two changes are observed; emission generally is reduced and its dependence on field direction becomes increasingly complicated. Concurrently, the collector current (left column of Fig. 2) is very strongly reduced as the field becomes perpendicular to the plane containing the grid axis and the filament (g–f plane) and is enhanced by as much as a factor of 2.5 for field directions lying within about 35° of the g–f plane. This collector current pattern is evident for fields as small as about 0.005 T. For larger fields minima developed at $\theta = 90°$ and 270° (field parallel to g–f plane), and at $\theta = (90^{+25}_{-17})°$ and $\theta = (270^{+25}_{-17})°$. In the gauge examined, four 0.5-mm-diam grid support wires were located at $\theta = (90 \pm 45)°$ and $(270 \pm 45)°$. Like Hammond and Riviere's[11] results at 0.2 T for a conventional triode, these last four minima may be due to interception, by the grid support wires, of a portion of the emission current before it can enter the interior of the grid. The collector and emission current measurements shown in Fig. 2 were also made at a base pressure of 5×10^{-8} Pa and at about 1000× this base pressure (i.e., 5×10^{-5} Pa). For any given field (B,θ), emission current was found to be the same at the highest and lowest pressure; this indicates that emission was pressure independent over the entire range. Insufficient data were obtained to permit precise characterization of the collector current pressure dependence. Presumably it is separable from the field dependence as was found for the case of field parallel to the grid axis (see Sec. III A 2) and by Hseuh[12] for low-field behavior in argon. In the present case, however, collector current $i_c(B,\theta)$, normalized by its value i_c^0 in zero applied field, was 5%–25% larger (depending on field) at the lowest pressure (5×10^{-8} Pa) than at the high end (5×10^{-5} Pa) of the pressure range. If the collector current is represented in the usual way as $X + pR$, where the x-ray current X and the gauge response R are now field dependent, then the above observation may be interpreted to mean that at the low end (5×10^{-8} Pa) of the pressure range the x-ray current is not negligible with respect to the true ion current.

The large negative collector currents (see Sec. III B) which developed for certain field directions at the higher field values (see 0.08 and 0.16 T data of Fig. 2) prompted the wall current measurements shown in both Fig. 3 and the right column of Fig. 2. Very low fields slightly enhanced the wall current, as shown by the positive slope at $B = 0$ for the i_w curves in Fig. 3. For fields greater than about 0.0075 T (and ignoring the regions where wall current becomes negative), the wall current remains positive but decreases gradually in a manner similar to the emission current. Certain combinations of field strength and direction resulted in negative wall currents, sometimes very large.

Comparison of the polar-plotted collector and emission currents (Fig. 2) shows that there is a real reduction in gauge sensitivity as the field becomes perpendicular to the g–f plane; the collector current is greatly reduced, whereas the emission current is reduced comparatively little. For field direction more nearly parallel to the g–f plane, gauge sensitivity is enhanced. As pointed out by Martin,[9] this reduction of the collector current to near zero when the field is perpendicular to the g–f plane may be easily understood. In this case, the magnetic field and the strong electric field ($\sim 4\times10^4$ V/m) in the gap between filament and grid are perpendicular and their combined action is expected to produce approximately cycloidal electron orbits in which a thermally emitted electron's net motion is a drift parallel to the filament's length. For perfectly uniform fields, the dimensions (altitude and spatial period) for these ideal orbits scale as E/B^2 so that for sufficiently large B (~ 0.02 T), the orbits do not penetrate into the interior of the grid. This would lead to very small positive ion collector current, as observed. On the other hand, when the magnetic field is more nearly parallel to the strong electric field between filament and grid, a significant number of the emitted electrons can be accelerated across the filament–grid gap, with little or no deflection by the magnetic force, and enter the grid with normal energy (~ 100 eV). Inside the grid, these energetic electrons experience the usual radial electric field plus the applied uniform magnetic field, and can be expected to execute orbits different from those for $B = 0$. If these new orbits have longer paths inside the grid cage, between the locations where an electron enters and exits, this could produce the observed enhancement of the collector current (and the gauge's sensitivity).

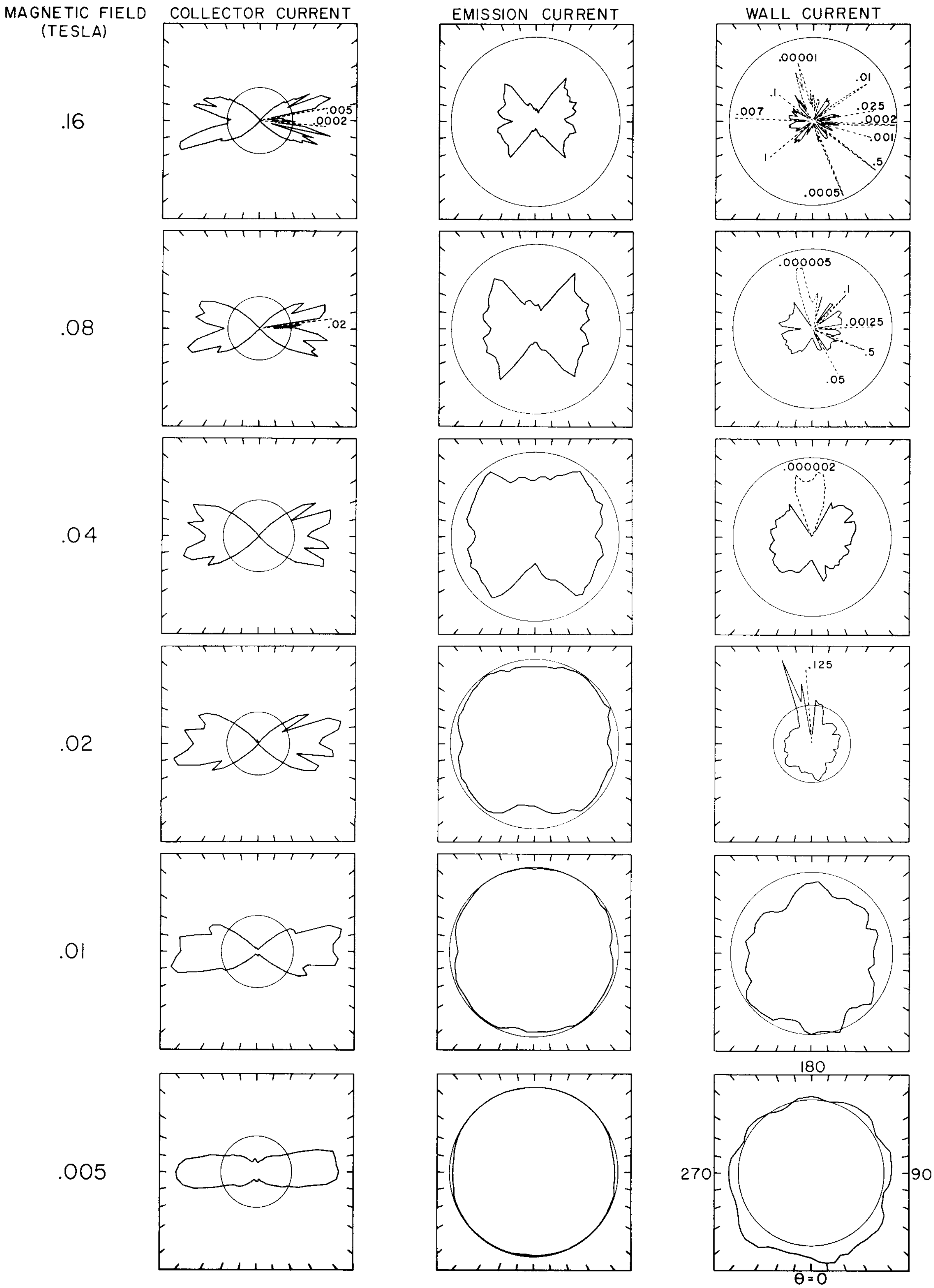

FIG. 2. Typical data for emission, collector, and wall current of the B–A gauge as functions of magnet rotation angle θ (refer to Fig. 1) for several values of magnetic field. The gauge was operated in a base vacuum of 1.2×10^{-7} Pa N_2 equivalent. Data were taken every 5°, except every 2.5° at 0.16 T. Negative currents are indicated by dashed lines (---) and adjacent numbers are the factors by which the negative current data have been reduced before plotting. In these linear-polar plots, the circles represent the zero magnetic field values 22 and 147 pA, and 1.05 mA, of collector, wall, and emission current, respectively. All data were obtained at a constant filament heater power of 7.6 W.

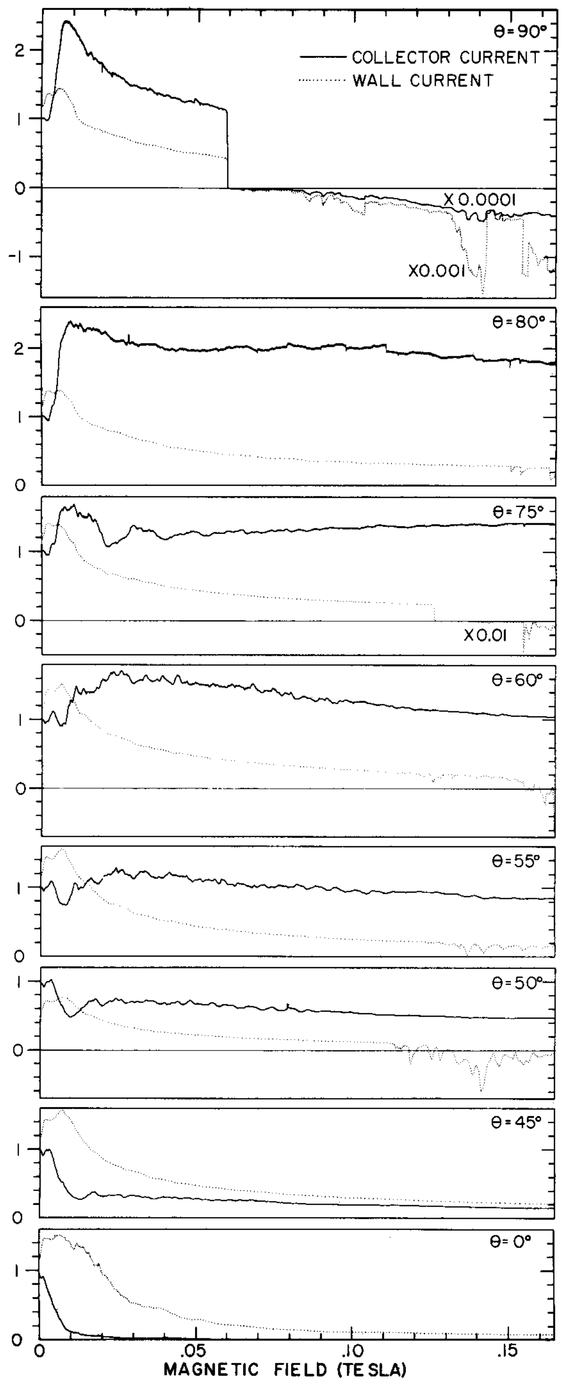

FIG. 3. Simultaneously recorded typical data, at a pressure of about 1.1×10^{-7} Pa N_2 equivalent, for collector (——) and wall (···) currents, as a function of field magnitude for several field directions perpendicular to grid axis [refer to Fig. 1 (b)]. On the linear ordinate scale, one corresponds to a collector current i_c of 19.7 pA and a wall current i_w of 123 pA with the exception of $\theta = 50°$ data for i_w, for which one corresponds to 246 pA wall current. The fine details in the positive collector current data were reproducible. Note the negative-going changes in i_w, and that portions of the data have been reduced before plotting.

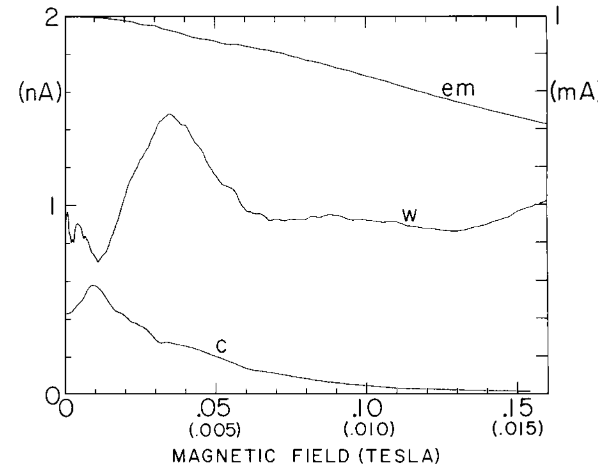

FIG. 4. Dependence of emission (em), collector (c), and wall current (w) on magnetic field magnitude for case in which field is *parallel* to grid axis. Gauge operated in base vacuum of 2.3×10^{-6} Pa N_2 equivalent (unbaked system for these data). For *collector current*, abscissa scale is expanded $10\times$ (field values in parentheses). Full scale ordinate represents 2 nA for wall and collector current (left) and 1 mA for emission current (right). Shape of curve c in Fig. 4 was found to also represent the field dependence of the data at 10 and $100\times$ base pressure, i.e., $i_c = pf_c(B)$, where p is pressure and $f_c(B)$ is a function of field strength. The curve w also represents the field dependence of the wall current data at 10 and $100\times$ base pressure, after subtraction of a small field-dependent current k, i.e., $i_w = k(B) + pf_w(B)$, where k ranges from 0.06 to 0.26 nA.

2. Magnetic field parallel to grid axis

As shown by the data in Fig. 4, with increasing field the emission current smoothly decreases to about 70% of the zero-field value at 0.16 T. The collector current rises to a maximum for a very weak field of about 0.001 T and for larger fields, decreases smoothly in a manner similar to the data at $\theta = 0°$ in Fig. 3.

The curves in Fig. 4 represent the dependence of emission and collector current on magnetic field over an approximate two order of magnitude pressure range: After measurement of the currents versus B at a base pressure of 2.3×10^{-6} Pa N_2 equivalent, N_2 was leaked into the continuously pumped vacuum chamber at such a rate that the gauge collector current value in zero magnetic field was either 10 or $100\times$ larger than its value at the base pressure. The current versus field measurements were then repeated. The three i_{em} vs B curves were indistinguishable. Thus, the magnetic field dependence of the emission current is independent of pressure, just as was found for the case of the field perpendicular to the grid axis (see Sec. III A 1). After normalizing by the corresponding zero-field value, the three collector current data sets were practically indistinguishable, indicating that over the range 2×10^{-6} to 2×10^{-4} Pa, the collector current has a separable dependence on pressure and magnetic field. The normalized wall current curves at 2.3×10^{-5} Pa and 2.3×10^{-4} Pa matched to within a few percent. However, wall current at the base pressure (shown in Fig. 4) was 8% to 30% larger than 1/10 or $1/100\times$ the wall current data at 10 or $100\times$ base pressure. This difference, which ranged from 0.06 to 0.26 pA, can be reasonably attributed to a pressure-independent but magnetic field-dependent current of electrons photoejected from the wall. These results show that, above about 2×10^{-5} Pa, wall current has a separable dependence on pressure and magnetic field.

The disadvantage of a large loss of sensitivity with increasing field strength for this particular orientation of the gauge (grid axis parallel to the field) may be offset somewhat by the fact that negative collector currents were never observed for this case even for B as large as 0.16 T (see Sec. III B below) and that the net magnetic force acting to deflect the filament should also be smallest for this case.

B. Negative currents

An interesting feature of the collector and wall current data shown in Figs. 2 and 3 for **B** perpendicular to grid axis is the development of negative currents, a phenomenon reported by many investigators. On the magnetic field scale of Fig. 3, this development was fairly smooth in some instances ($\theta = 50°$ data for i_w) and very abrupt in others ($\theta = 90°$ data for both i_c and i_w). In the $\theta = 55°$ and $80°$ pictures for i_w (Fig. 3), i_w exhibits negative-going changes but does not actually change sign. As functions of field direction (see Fig. 2) the negative currents appeared in very small angular ranges in some cases (e.g., i_w at 0.02 T and i_c at 0.08 T) and in a relatively broad range in other instances (e.g., i_w at 0.04 T). It is evident from the data in Fig. 2 that negative collector current developed only when the field was very nearly parallel to the *g–f* plane, whereas the extremely large negative wall currents occurred when the field was more nearly perpendicular to the *g–f* plane. This apparently characteristic feature of the negative collector and wall currents was observed again when the 0.04, 0.08, and 0.16 T measurements of Fig. 2 were repeated with the second filament [at $\theta = 180°$ in Fig. 1(b)] which defined a new *f–g* plane, at right angles to the one shown in Fig. 1(b). In either case, the unheated filament was at the same potential as one end of the hot filament. In some instances the magnitude of the negative wall or collector current exceeded the corresponding zero-field value by a factor of 2×10^5 (i_w at 0.08 T in Fig. 2) and 5×10^3 (i_c at 0.16 T), respectively. The negative currents appeared to be roughly independent of pressure. However, because these currents tended to change with time for fixed **B** field and seemed also to depend on the history of the **B** field, no attempt was made to systematically study the effect of pressure on the negative currents.

During initial examination of the gauge behavior for the field *parallel* to the grid axis, the wall current abruptly became negative on several occasions as the field was increasing through a value of ~ 0.15 T. However, the behavior was not reproducible; the magnitude of the negative current became smaller for each occurrence. After about an hour of gauge operation in the field, the wall current was small and positive again, with no indication of negative-going changes (see Fig. 4). Negative (or negative going) *collector* currents were never observed for any value of field parallel to the grid axis.

The negative currents were further investigated by biasing the wall. For example, at $B = 0.04$ T and $\theta = 195°$ (refer to Fig. 2) it was found that a wall bias of -30 V was required to reduce the negative wall current to zero. Since the filament was at $+50$ V, this implies that some electrons acquire kinetic energies 80 eV in excess of that expected from the dc gauge potentials. At $\theta = 270°$ and $15°$ for $B = 0.04$ T, a wall bias of more than $+34$ and $+43$ V, respectively, would cause the wall current to become negative, indicating that in this case, there are, respectively, some electrons with kinetic energies 16 and 7 eV in excess of that expected from the dc gauge potentials. The excess-energy electrons may be due in some way to the action of an oscillating electron space charge,[2] because the applied static magnetic field cannot change an electron's speed, and the high energies are impossible in principle for the static electric field associated with the dc gauge potentials alone (no space charge).

The phenomenon of negative collector currents is not unique to the B–A structure. It was reported by Barkhausen and Kurz[13] as early as 1920 for a conventional hot-cathode triode operated with no applied magnetic field. In the present work, negative collector currents were also observed during operation of a normally biased conventional triode gauge in a uniform magnetic field directed perpendicular to the grid axis. The physical process leading to the negative collector and wall currents observed in the present work may be the same process which produces anomalous anode current in a cylindrical magnetron[5] or excessive cut-off current in the hot-cathode magnetron gauge,[2] and the ionization gauge of Conn and Daglish.[14]

C. Oscillations

Oscillatory components in the collector and wall currents were observed with a 1-GHz bandwidth power spectrum analyzer and, for real-time display, a 200-MHz bandwidth oscilloscope. At 0.3-MHz resolution, the frequency spectra of the oscillations were characterized by components with bandwidths of 0.3 MHz or less. For magnetic field parallel to the *g–f* plane, the frequencies were confined to about nine distinct intervals in the range 2–650 MHz, the intervals being roughly 1 to 5 MHz wide. In this case, most of the frequencies appeared to be harmonics of about 65 MHz although signals at 65 and 130 MHz were not detected. When the field was perpendicular to the *g–f* plane, the observed frequencies were in the vicinity of 6, 62, 86, 122, and 162 MHz with no clear pattern of harmonics. For any particular field (B,θ), there were usually only one or two components present. In some cases, however, the amplitude and frequency of the component would jitter rapidly with time, producing a power spectrum which resembled a band of noise. As the magnetic field was changed (B or θ), there were generally either smooth changes in amplitude of a given component, sometimes accompanied by slight shifts in frequency or, very abrupt changes in which one component vanished and one of a different frequency appeared. Real-time display of the currents showed the ac component of collector current to range from a fairly pure sinusoidal oscillation, to an amplitude-modulated oscillation (5 to 15 MHz modulation frequency), to a very complex waveform. The corresponding wall current waveform contained the same highest frequency component as the collector current, but was generally more complex. Changing the grid or filament bias voltages also influenced the amplitude and frequency of oscillations but these effects were not investigated in detail. No oscillations were detected for any value of field parallel to the grid axis.

On the basis of the present investigation, the oscillations and negative currents appear to be related phenomena. Generally, abrupt changes in amplitude or frequency of the oscillations coincided with abrupt changes in the collector and/or wall current and, negative dc collector and/or wall currents were always accompanied by ac components. Since the collector and wall are not electron sources like the hot filament, the high-frequency oscillating currents must be reactively coupled to the collector and wall. This implies an oscillating space charge within the gauge. Together, these observations strongly suggest a mechanism whereby an oscillating space charge is able to accelerate some electrons to velocities higher than possible with the static electric field due to the gauge potentials alone. Even if no electron acquires sufficient extra energy to reach the collector, the electron energy distribution may be sufficiently altered during the occurrence of oscillations to significantly change the gauge sensitivity. It is quite interesting that one of the earliest investigations[13] of negative currents and oscillations was carried out with an evacuated hot-cathode triode device *not* operated in a magnetic field. However, oscillations were never detected for $\mathbf{B} = 0$ in the present study. In the work of Redhead[15] with glass tubulated B–A gauges (also not operated in a magnetic field) 40- to 80-MHz oscillations were detected, and negative collector currents were in fact attributed to the action of the rf field on electrons.

IV. SUMMARY

(1) For fixed field direction, emission current decreased smoothly as field magnitude was increased; its dependence on field direction (azimuth) about the grid axis became increasingly strong and complicated as field magnitude was increased. These effects were pressure independent over the range studied (5×10^{-8} to 2×10^{-4} Pa).

(2) For field parallel to grid axis (and presumably for other field directions as well), it was determined that the collector current has a separable dependence on pressure and magnetic field.

(3) Because of their erratic behavior and large magnitude, the occurrence of negative collector currents will restrict the ranges of field magnitude and direction for which gauge operation is feasible.

(4) The very strong dependence of the gauge currents on field direction with respect to the *g–f* plane arises from a lack of rotational symmetry about the grid axis. Using a circular filament, as was done by Hammond and Riviere,[11] appears to be a good way to reduce this directional dependence of the sensitivity. An extractor gauge with this filament geometry is commercially available, and would be a logical choice of gauge for further investigation of this point.

(5) The phenomenon of negative collector and wall currents appears to be a subject worthy of further investigation.

ACKNOWLEDGMENT

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